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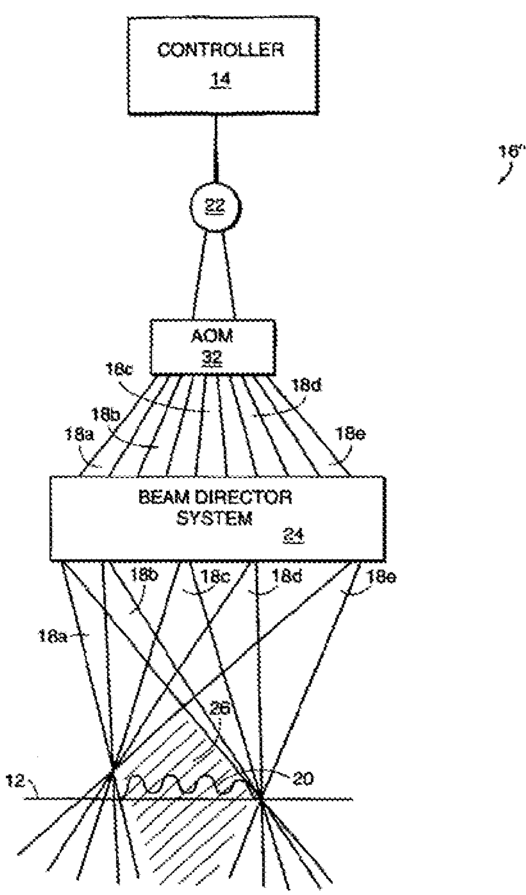

(57) Abstract: A method and apparatus for projecting interference patterns using an acousto-optic modulator is described. The apparatus includes a laser, an acousto-optic modulator and an optical beam director system. The acousto-optic modulator is used to separate the laser beam into multiple beams which are directed onto a target plane. The result is a pattern determined by the relative amplitude and phase between the beams. The intensity at a point in the pattern varies due to the Doppler-shifted frequencies of the beams. The pattern is frozen in time by synchronously controlling the diffractive modulator and amplitude modulating the laser beam. Spatial phase is adjusted by controlling the phase of the laser amplitude modulation waveform with respect to the AOM control signal.

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ACOUSTO-OPTIC LIGHT PROJECTOR

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH

This invention was made with government support under U.S. Air Force Contract No. F19628-95-C-0002 awarded by the National Aeronautics and Space Administration (NASA)/Advanced Geosynchronous Studies Program. The government may have certain rights in the invention.

FIELD OF THE INVENTION

The invention relates to the field of optical modulation and more specifically to the field of optical pattern projection.

BACKGROUND OF THE INVENTION

High resolution projection systems can be used to project detailed images onto target planes. For example, these lithographic projection systems are used in the fabrication of semiconductor circuits by imaging a mask onto the surface of a semiconductor wafer coated with a photoresist. Exposed regions of photoresist within the projected image are chemically altered and react differently to subsequent chemical or physical treatment of the wafer than unexposed regions. A series of masks and intervening treatments are used to form layers on the wafer having the required electronic structures.

The masks used in the process are expensive and time consuming to produce. Further changes required in the circuitry after the mask is produced typically require a new mask to be created. The complex optical systems used in the process are also expensive and require significant maintenance. High numerical aperture lenses have small depths of field and are limited in contrast at higher spatial frequencies. The demanding requirements of the semiconductor industry for higher resolution, contrast, depth of field and optical efficiency are

coupled with a desire to minimize distortion. Physical constraints inherent in projection lens systems will limit further performance improvements.

A synthetic aperture projection system can be used to avoid the problems associated with the use of physical masks and lenses used in conventional lithography. The synthetic aperture projection system uses a discrete set of controllable beam sources to generate the desired pattern at an image plane. More complex patterns can be achieved as the number of beam sources is increased. Unfortunately, the cost and design complexity also increase according to the number of beams used.

Accordion Fringe Interferometry (AFI) is another application that requires pattern projection. AFI is a non-contact method for producing three-dimensional surface maps of objects. The method relies on projecting interference patterns on a surface to be measured. A set of interference patterns is produced by illuminating the surface with optical radiation from a pair of point sources at known separations. Unfortunately, the speed, measurement accuracy and stability, and cost of an AFI projection system are limited by the point source motion control system which typically relies on translation of mechanical and optical elements.

SUMMARY OF THE INVENTION

The invention relates to a method and apparatus for generating a substantially stationary interference pattern. A multi-beam pattern projector is used to create the interference pattern on an image plane in a region of beam overlap. Independent control of the beam parameters of each beam using a single acoustic wave diffractive device simplifies the design and implementation of the multi-beam pattern projector and reduces its cost. The multi-beam pattern projector offers many advantages over projectors that rely on motion of mechanical or optical components, including speed, improved accuracy, stability and repeatability.

The method includes the steps of providing a source of a coherent radiation beam, positioning an acoustic wave diffractive modulator to receive the beam, generating at least two

coherent output beams using the acoustic wave diffractive modulator, creating a region of beam overlap using at least two of the coherent output beams and controlling the acoustic wave diffractive modulator to modulate at least one of the coherent output beams to generate the substantially stationary interference pattern.

In one embodiment the method includes the step of positioning a focusing element near the acoustic wave diffractive modulator to focus at least one of the coherent output beams. In another embodiment the method includes the step of modulating the amplitude of the coherent radiation beam from the source. In another embodiment the method includes the step of providing an electrical signal for controlling the acoustic wave diffractive modulator. In yet another embodiment the method includes the step of modulating the electrical signal to control a characteristic of the interference pattern.

The apparatus includes a coherent optical beam source generating a coherent beam, an acoustic wave diffractive modulator which generates at least two output beams from the coherent beam, and an optical beam director system directing at least one of the output beams to form a substantially stationary interference pattern in a region of beam overlap.

In one embodiment the coherent optical beam source has a source drive input and generates an amplitude modulated coherent optical beam in response to an electrical signal received at the source drive input. In another embodiment the apparatus includes an amplitude modulator in optical communication with the coherent optical beam source. In yet another embodiment the apparatus includes a focusing element.

BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing and other objects, features and advantages of the invention will become apparent from the following more particular description of preferred embodiments of the invention, as illustrated in the accompanying drawings, in which:

FIG. 1 is a highly schematic diagram of a multi-beam pattern projector.

FIG. 2 is a highly schematic diagram of a multi-beam pattern projector with multiple beam modulators.

FIG. 3 is a highly schematic diagram of an embodiment of a system constructed in accordance with the present invention.

FIG. 4 is a schematic diagram of an acousto-optic modulator system used to generate a diffracted beam.

FIG. 5 is a schematic diagram of an acousto-optic modulator system used to generate an angularly tunable diffracted beam.

FIG. 6 is a schematic diagram of an acousto-optic modulator controlled with a compound drive signal.

FIG. 7 is a diagram of an embodiment of a pattern projector system according to the present invention.

FIG. 8 is a plot of system electrical signals according to the embodiment of FIG. 7.

FIG. 9 is another plot of system electrical signals according to the embodiment of FIG. 7.

FIG. 10 is a highly schematic diagram of an accordion fringe interferometric measurement system according to the present invention.

DETAILED DESCRIPTION OF THE INVENTION

An optical synthetic aperture system 16 is used to project a light pattern 20 onto at an image plane 12 as shown in Fig. 1. The embodiment of the system 16 as shown includes fifteen optical radiation sources 10(a-o) (only five sources 10(a-e) are shown for clarity). Each source

10 is controlled by a controller 14 to produce a respective optical beam 18 (a-o) having a predetermined intensity, phase and polarization. The beams 18 are directed to the image plane 12 such that the beams 18 overlap and interfere to form the light pattern 20. Referring to FIG. 2, another synthetic aperture system 16' includes a beam modulator 50 (a-o) in the path of each beam 18. The controller 14 generates a control signal for each beam modulator 50 to generate beams 18 having the desired intensity, phase and polarization.

Referring to Fig. 3, an acousto-optic light projector 16'' according to the present invention is based on a synthetic aperture system having a single pulsed laser source 22 and a single acousto-optic modulator (AOM) 32. The AOM 32 receives a single beam 18 from the pulsed laser source 22 and generates fifteen modulated laser beams 18(a-o) (only five beams 18(a-e) are shown for clarity). The number of modulated beams 18 required in the projector 16'' is dependent in part on the complexity of the light pattern 20 to be generated. A beam director system 24 (e.g., mirrors and lenses) directs the beams 18 to a region of overlap 26 from a ring of discrete locations within the beam director system 24.

Referring to Fig. 4, an acousto-optic modulator 32 includes a crystal 34 with a piezo-electric transducer (PZT) 36 at one end. An RF control signal 38 drives the PZT 36 which generates a traveling sound wave 40 in the crystal 34. An acoustic absorber 42 at the end of the crystal 34 opposite the PZT 36 is used to prevent undesirable reflection of the sound wave 40. The pressure variations along the sound wave 40 cause corresponding variations in the local refractive index of the crystal 34. Thus the periodic RF control signal 38 generates a traveling phase grating in the crystal 34.. A laser beam 44 passing through the crystal 34 is diffracted at an angle θ determined by the effective grating spacing λ_s which corresponds to the periodic spacing of the refractive index variations in the crystal 34. The amplitude of the acoustic signal 40 determines the amount of optical power transferred from the zero order beam 46 to the first order beam 48 exiting the crystal 34. The angle can be varied by tuning the sinusoidal electrical signal

38 to a different frequency as shown in Fig. 5. The change in the first order angle $\Delta\theta$ is approximated by

$$\Delta\theta \approx \frac{\lambda \cdot \Delta f_s}{n \cdot v_s}$$

where λ is the wavelength of the laser beam 44 in free space, Δf_s is the change in the drive signal frequency, n is the index of refraction of the crystal 34 and v_s is the speed of sound in the crystal 34.

A superposition of several single frequency signals 38(a-c) by a summer 28 results in the superposition of multiple acoustic wavefronts 40, and generates multiple angularly-separated first order beams 48(a-c) as shown in Fig. 6. The amplitude, frequency and phase of each component 38(a-c) of the drive signal 38 can be independently controlled. As a result, the amplitude, direction and relative phase of each first-order beam 48(a-c) can also be controlled. Because the pressure variations across the crystal 34 are not stationary, the first-order beams 48 are Doppler shifted with respect to the zeroth order beam 46.

Referring to FIG. 7, an embodiment of an acousto-optic light projector 16'' includes a laser diode 90, a laser diode collimating lens 92 and an AOM 32. A fan mirror array 94 directs each first order beam 48(a-o) from the AOM 32 to a respective mirror (mirrors are not shown for clarity) in a ring mirror array 96. The beams 48 are reflected from the ring mirror array 96 to a target 98 (e.g., a wafer coated with photoresist). A digital RF synthesizer 100 generates an amplitude modulation (AM) waveform 62 for modulating the output power of the laser diode 90, a control signal 102 and a local oscillator signal 54. The control signal 102 is mixed with the local oscillator signal 54 at a mixer 104. The mixer output signal 58 is amplified by power amplifier 106 and high pass filtered by filter 108. The filtered RF signal 38 is used to drive the AOM 32. The synthesizer output signals 54, 62 and 102 can quickly and accurately be changed to modify the projected pattern 20 or generate a new projected pattern 20. A target camera 110

and objective lens system 112 are used to obtain images of the target 98 for alignment of the projected pattern 20 with target features.

Referring to FIG. 8, a control signal 102 having fifteen frequency components 52(a-o), with each component 52 spaced from its nearest frequency component 52 by 3 MHz. The control signal 102 is mixed with a local oscillator signal 54 to produce a mixer output signal 58. Using an AOM 32 with an operational range from 50 to 100 MHz, the mixer output signal 58 generates fifteen pure acoustic tones 60(a-o) in the AOM crystal 34 after amplification and high-pass filtering. Each tone 60 corresponds to a traveling phase grating in the crystal 34 and one of the diffracted beams 48 from the AOM 32. Each diffracted beam 48 has a Doppler-shifted frequency determined by its corresponding mixer output frequency component 60. Each pair of diffracted beams 48 from the AOM 32 interferes in the region of beam overlap 26 to form a fringe pattern 20 which travels across the region of overlap 26 at a speed proportional to the difference frequency between the respective tones 60. Thus the intensity at a point in the pattern 20 oscillates in intensity at the difference frequency of the two tones 60. The apparent contrast of the interference pattern 20 is reduced by fringe motion. If the exposure time is a fraction of the period of the highest difference frequency (i.e., the frequency difference between the highest frequency and lowest frequency tones 60o and 60a, respectively) the blurring effect of fringe motion is substantially suppressed.

The interference pattern 20 is made to appear stationary by amplitude-modulating the laser output beam 44 synchronously with the AOM control signal 38. Referring to FIG. 9, the laser 90 is amplitude-modulated according to an AM waveform 62 such that the pulsewidth PW of the modulated laser output beam 44 is less than the period T of the highest difference frequency signal 64. The spatial phase of the pattern 20 can be precisely controlled by changing the phase (e.g., changing the delay) of the AM waveform 62 with respect to the AOM control

signal 38 or by changing the phase of an AOM control signal component 60(a-o) with respect to the other components 60(a-o) or the AM waveform 62.

The optical intensity of the projected pattern 20 is a function of the amplitude modulated laser output beam 44. The output power capability of the pattern projector 16'' limits the size of the target 98 and is a major factor in the total cost of the projector system 16''. Amplitude modulation results in the appearance of a stationary pattern 20 with contrast that can range between 0% and 100%. Short laser pulses are not necessary, however, to freeze the pattern 20. The choice of the amplitude modulation waveform 62 is determined in part by the desired contrast in the projected pattern 20 and the available optical power of the laser beam 44. For continuous-wave (CW) lasers, the tradeoff between contrast and light intensity in the pattern 20 is nonlinear. For example, halving the duty cycle of a square wave AM signal 62 from 10% to 5% eliminates half the laser power but does not significantly change the contrast. Furthermore, some AM waveforms 62 are preferred based on both contrast and light intensity. The square wave offers the best performance because it is the most compact in the time domain for a fixed optical power, resulting in the least variation in the relative phases of the interfering beams 48 that generate the projected pattern 20. Pulsed lasers can be used to create a "pulsed interference pattern." Pulsed lasers concentrate all of their energy into narrow pulses, typically a small fraction of the highest difference frequency (i.e., nanosecond duration pulses), and can be generated at the difference frequency (or at a fraction of the difference frequency) of the interfering beams 48 resulting in patterns having apparent contrast values near 100%.

Another application for the light projector of the present invention is in the field of AFI. AFI is based on a technique that can be used to generate a sequence of fringe patterns 20 on a surface so that the surface profile can be determined. The sequence of fringes 20 includes fringe patterns 20 with different fringe spacings which are determined by the relative spacing between two source points. Referring to the embodiment shown in FIG. 10, an AOM 32 is used in an AFI

system 84 to project a light pattern 20 onto the surface of an object 86. The AFI system 84 includes a laser source 114, an AOM 32 and a lens 66. The AOM 32 generates two angularly-separated beams 48a and 48b. If the beams 48a and 48b are collimated, the lens 66 forms a point image P_1 and P_2 of each beam 48a and 48b, respectively, in the focal plane 68 of the lens 66. These point images P_1 and P_2 act as the source points required for performing AFI. The separation a between the point images P_1 and P_2 is an approximately linear function of the angular separation α of the diffracted beams 48a and 48b for small angles. The AOM 32 is driven with a compound signal 70 generated by multiplier 72 which multiplies a sinusoid 74 having a variable frequency f_m by a sinusoid 76 with a fixed frequency f_c. By adjusting f_m, the separation of the source points P_1 and P_2 can be adjusted about a point of symmetry 78 from zero separation to the maximum separation permitted by the bandwidth of the AOM 32. The resulting fringe pattern 20 thus expands or contracts as required for AFI measurements.

The interference pattern 20 generated by the AFI system 84 is not readily observable with CW laser light because of the relative Doppler shift between the beams 48a and 48b. Thus, amplitude modulation of the laser source 22 with a pulsewidth PW less than the period T of the difference frequency $2f_m$ of the two beams 48a and 48b freezes the pattern 20 at a particular spatial phase. The spatial phase of the fringes 20 can be precisely controlled by changing the phase (e.g., changing the delay) of the laser drive signal 80 with respect to the AOM control signal 70.

What is claimed is:

CLAIMS

1. A method for generating a substantially stationary interference pattern, comprising the steps of:

a) providing a source of a coherent radiation beam;

b) positioning an acoustic wave diffractive modulator to receive said coherent radiation beam;

c) generating two output beams of coherent radiation from said coherent radiation beam using said acoustic wave diffractive modulator;

d) creating a region of beam overlap using said two output beams of coherent radiation; and

e) controlling said acoustic wave diffractive modulator to modulate one of said two output beams of coherent radiation.

2. The method of claim 1 wherein step d) comprises positioning a focusing element proximate to said acoustic wave diffractive modulator to focus at least one of said two output beams of coherent radiation to a respective coherent point source.

3. The method of claim 1 wherein step e) comprises modulating the amplitude of one of said two output beams of coherent radiation.

4. The method of claim 1 further comprising the step of modulating the amplitude of said coherent radiation beam from said source.

5. The method of claim 1 wherein said region of beam overlap includes a target.

6. The method of claim 1 wherein the step of generating two output beams of coherent radiation comprises the step of providing an electrical signal for controlling said acoustic wave diffractive modulator.

7. The method of 6 further comprising the step of modulating said electrical signal to control a characteristic of said interference pattern.

8. The method of claim 7 wherein said characteristic is the spatial phase of said interference pattern.

9. The method of claim 7 wherein said characteristic is the spatial frequency distribution of said interference pattern.

10. The method of claim 7 wherein the step of modulating said electrical signal controls the amplitude of one of said two output beams of coherent radiation.

11. The method of claim 7 wherein the step of modulating said electrical signal controls the phase of one of said two output beams of coherent radiation.

12. The method of claim 7 wherein the step of modulating said electrical signal controls the frequency of one of said two output beams of coherent radiation.

13. The method of claim 7 wherein the step of modulating said electrical signal controls the angle of one of said two output beams of coherent radiation.

14. An apparatus for generating a substantially stationary interference pattern in a region of beam overlap comprising:

a coherent optical beam source generating a coherent optical beam;

an acoustic wave diffractive modulator in optical communication with said coherent optical beam source, said acoustic wave diffractive modulator generating two output beams from said coherent optical beam, one of said two output beams being a modulated beam; and

an optical beam director system in optical communication with said acoustic wave diffractive modulator, said optical beam director system directing one of said two output beams to form a substantially stationary interference pattern in a region of beam overlap.

15. The apparatus of claim 14 further comprising an amplitude modulator in optical communication with said coherent optical beam source.

16. The apparatus of claim 14 wherein said coherent optical beam source comprises a source drive input, said source generating an amplitude modulated coherent optical beam in response to an electrical signal received at said source drive input.

17. The apparatus of claim 14 wherein said coherent optical beam source comprises a laser.

18. The apparatus of claim 14 wherein said optical beam director system comprises a focusing element.

19. The apparatus of claim 14 wherein said acoustic wave diffractive modulator is an acousto-optic modulator.

20. The apparatus of claim 14 wherein said acoustic wave diffractive modulator is a surface-acoustic-wave device.

21. The apparatus of claim 14 wherein said region of beam overlap comprises at least a portion of the surface of an object.

22. The apparatus of claim 14 wherein said region of beam overlap comprises at least a portion of the volume of an object.

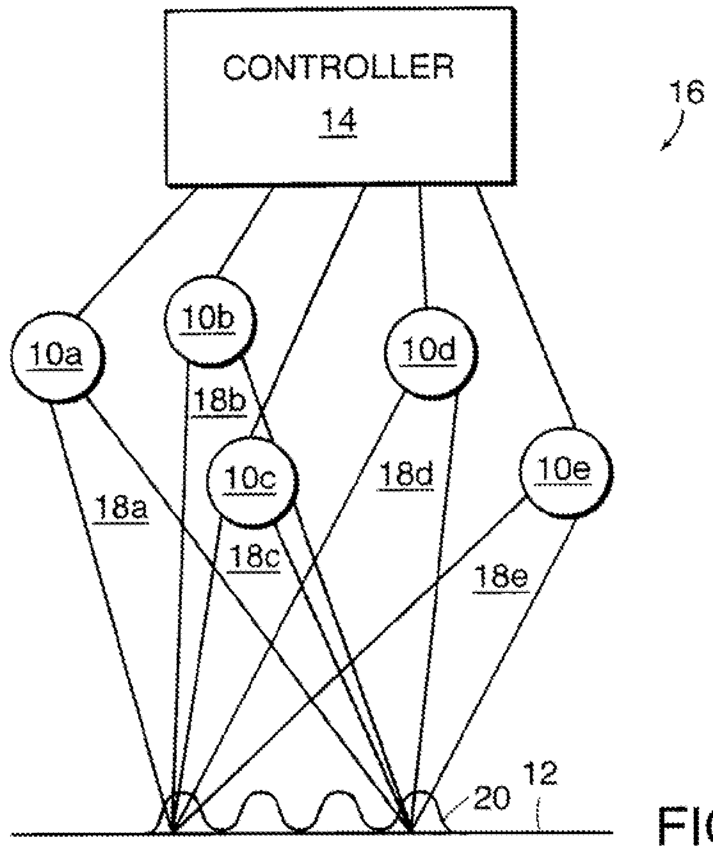
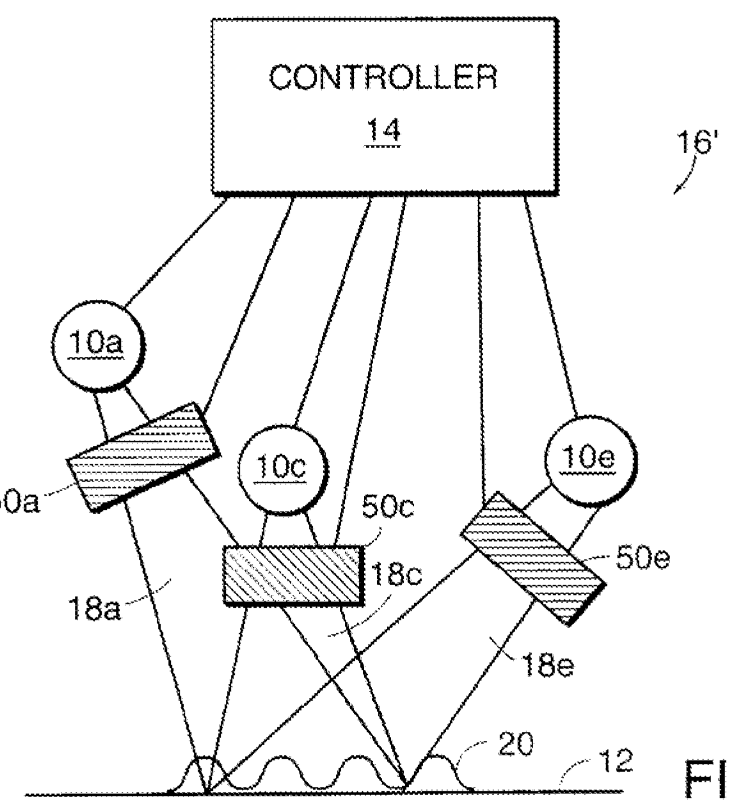

CONTROLLER
14
16
10a
10b
10c
10d
10e
18a
18b
18c
18d
18e
20
12

FIG. 1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16'
10a
10c
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50a
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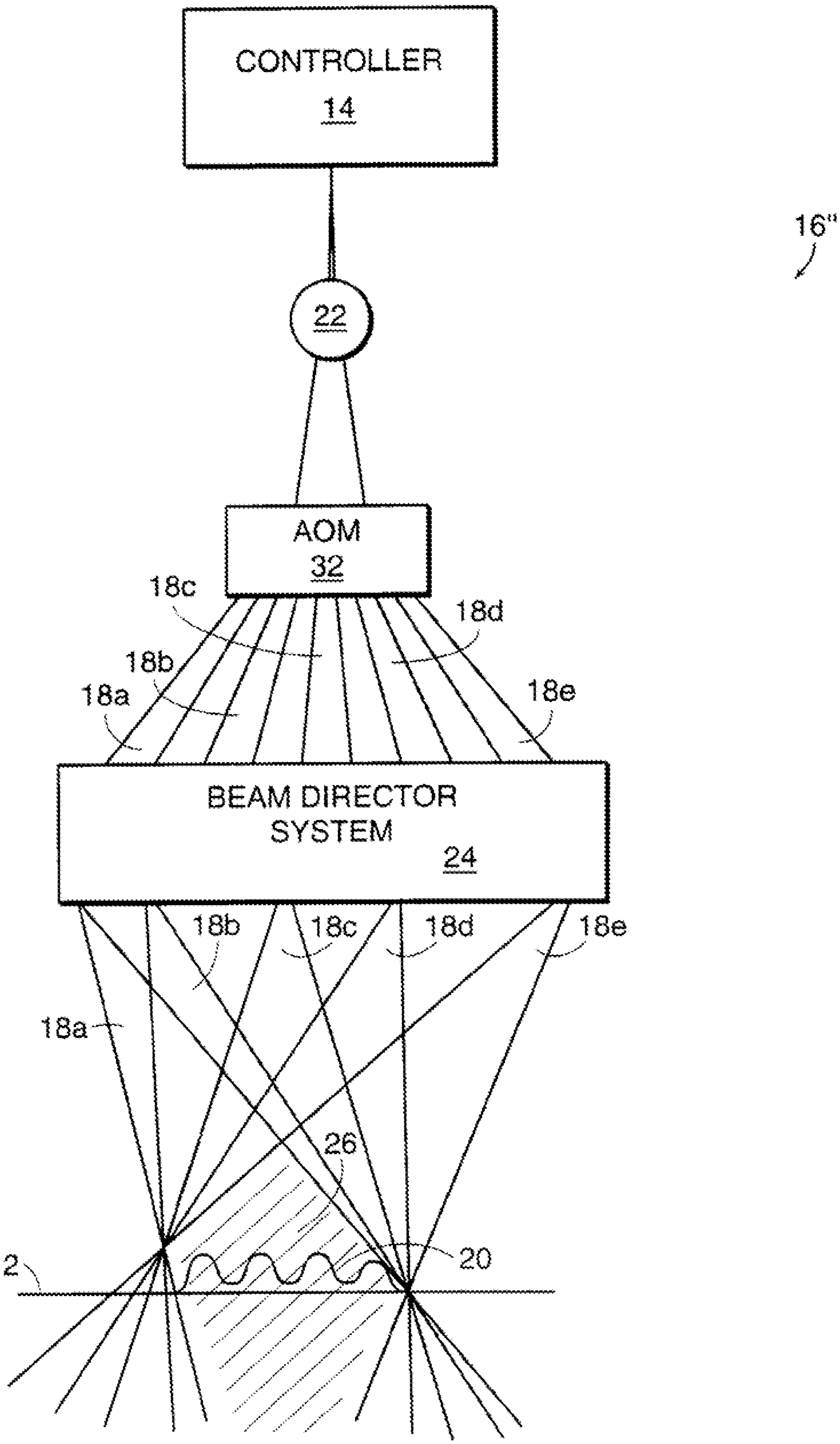
18a
18c
18e
20
12

FIG. 2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16"
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AOM
32
18c
18d
18b
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18e
BEAM DIRECTOR
SYSTEM
24
18b
18c
18d
18e
18a
26
12
20

FIG. 3

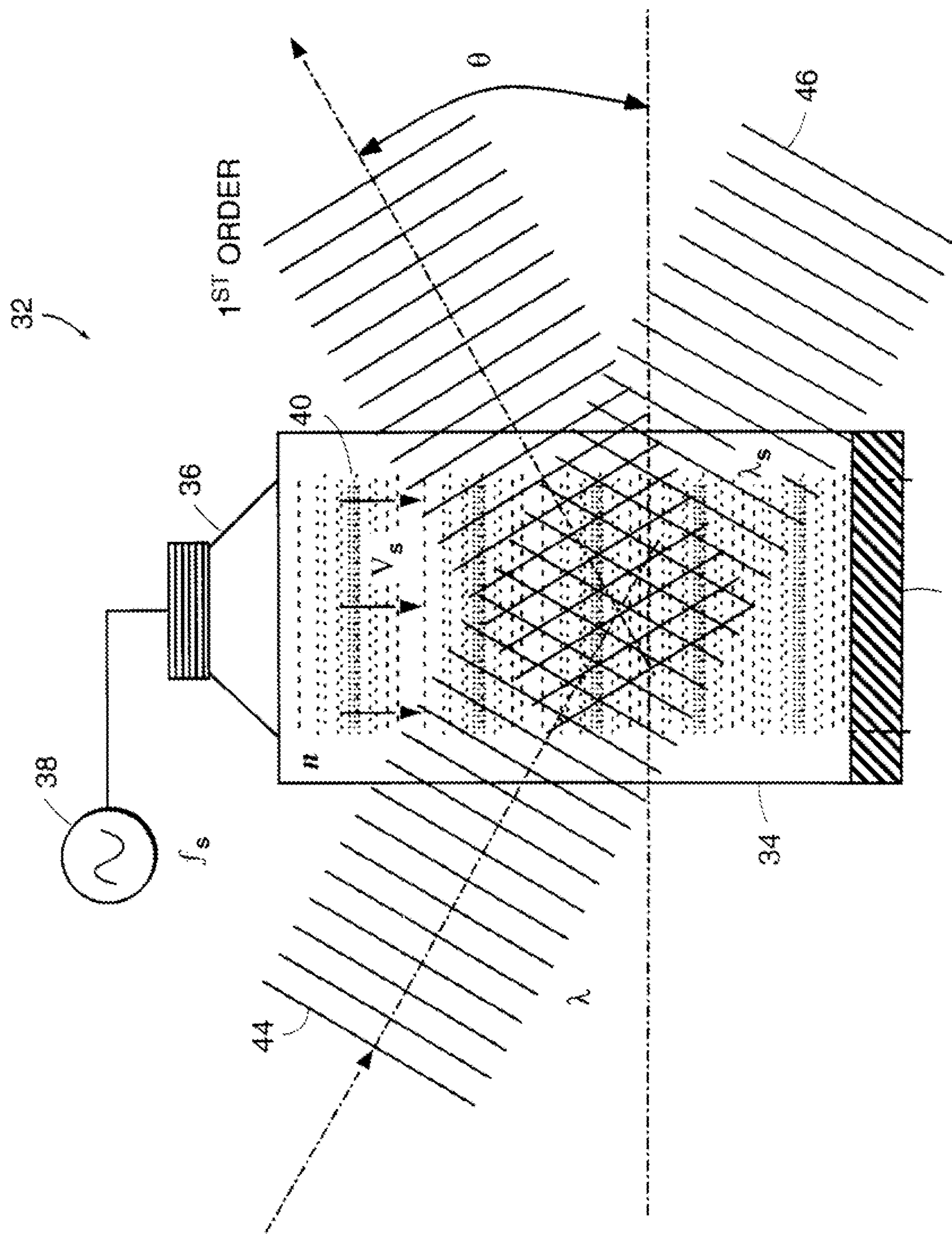


FIG. 4

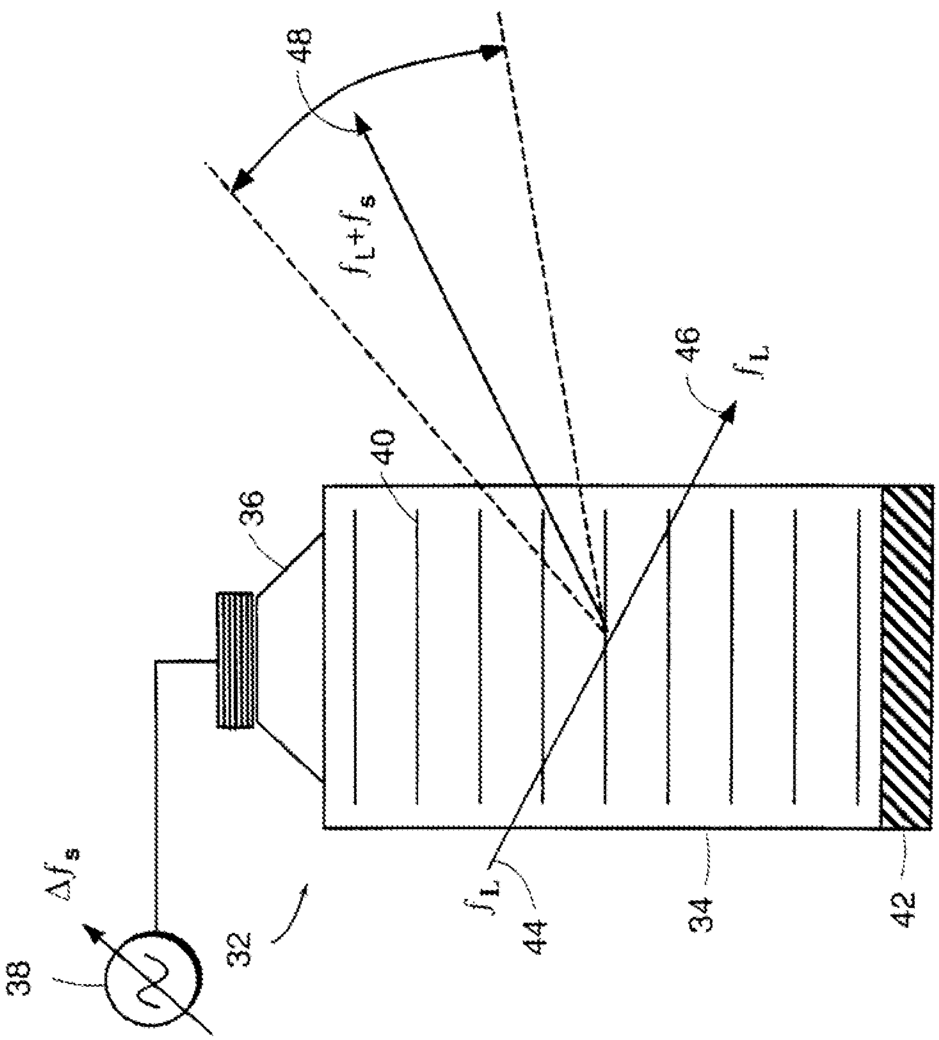
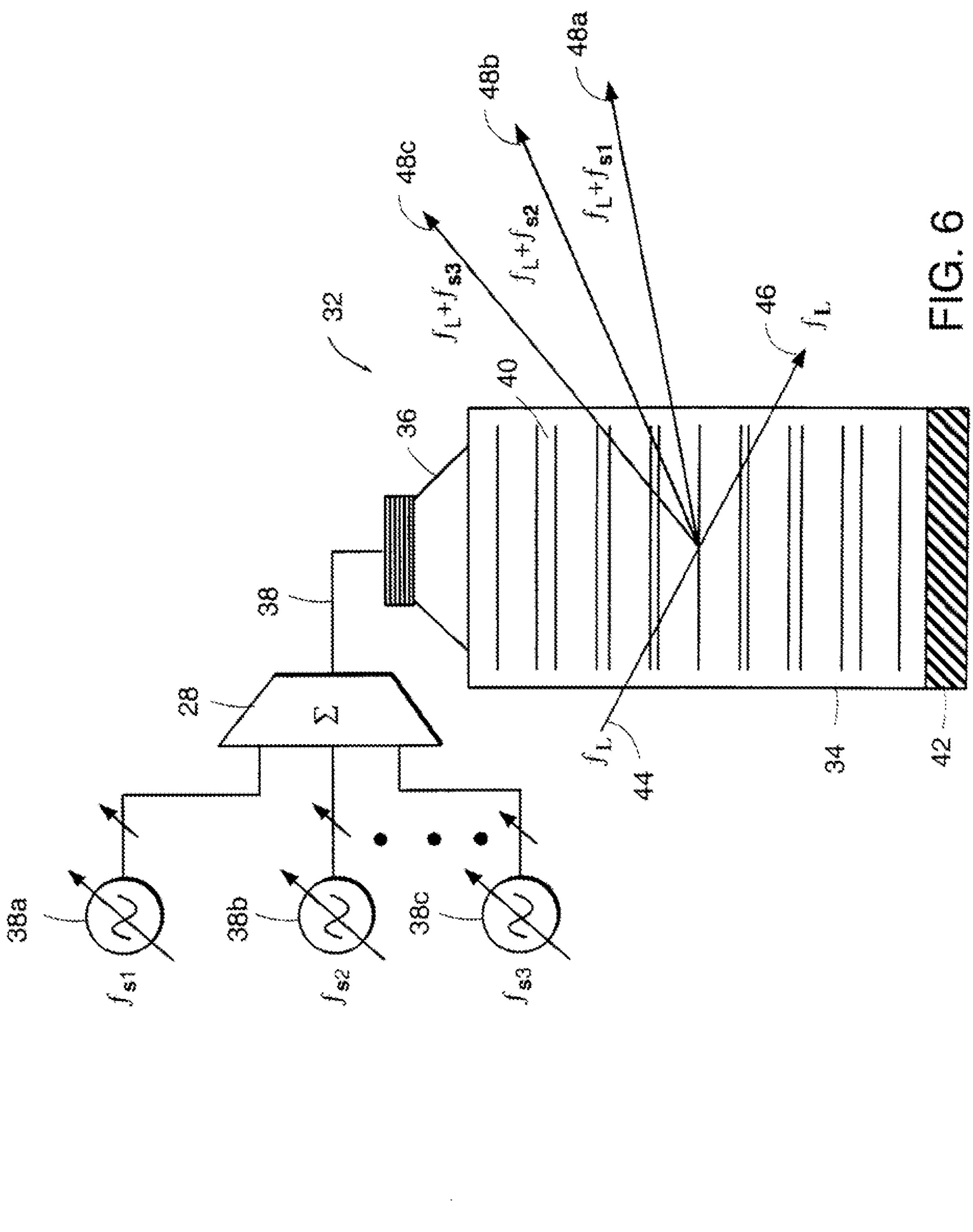


FIG. 5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38a
38b
38c
f_{s1}
f_{s2}
f_{s3}
28
Σ
38
36
40
34
42
44
46
f_L
f_L
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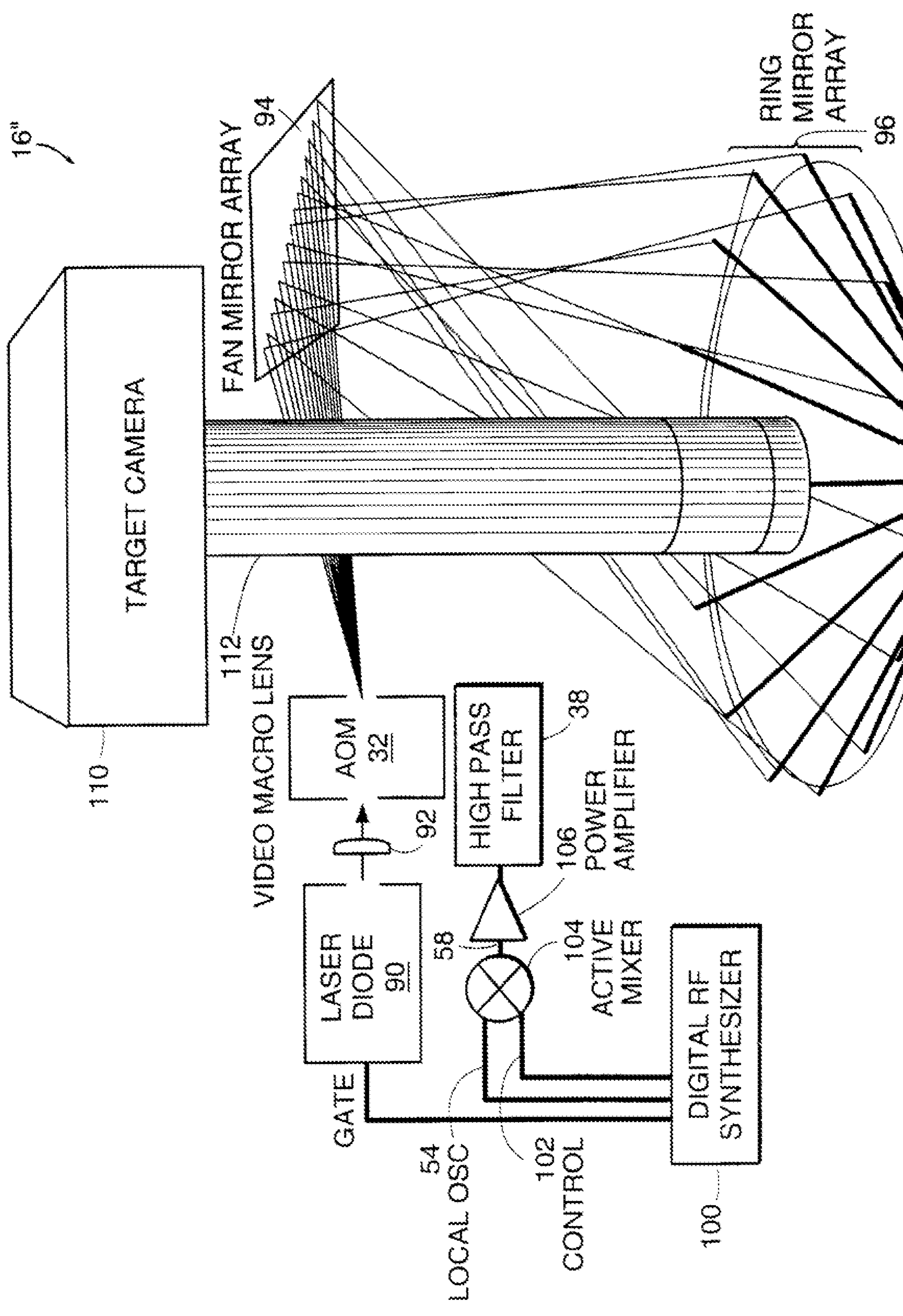
f_L+f_{s2}
f_L+f_{s3}
48a
48b
48c

FIG. 6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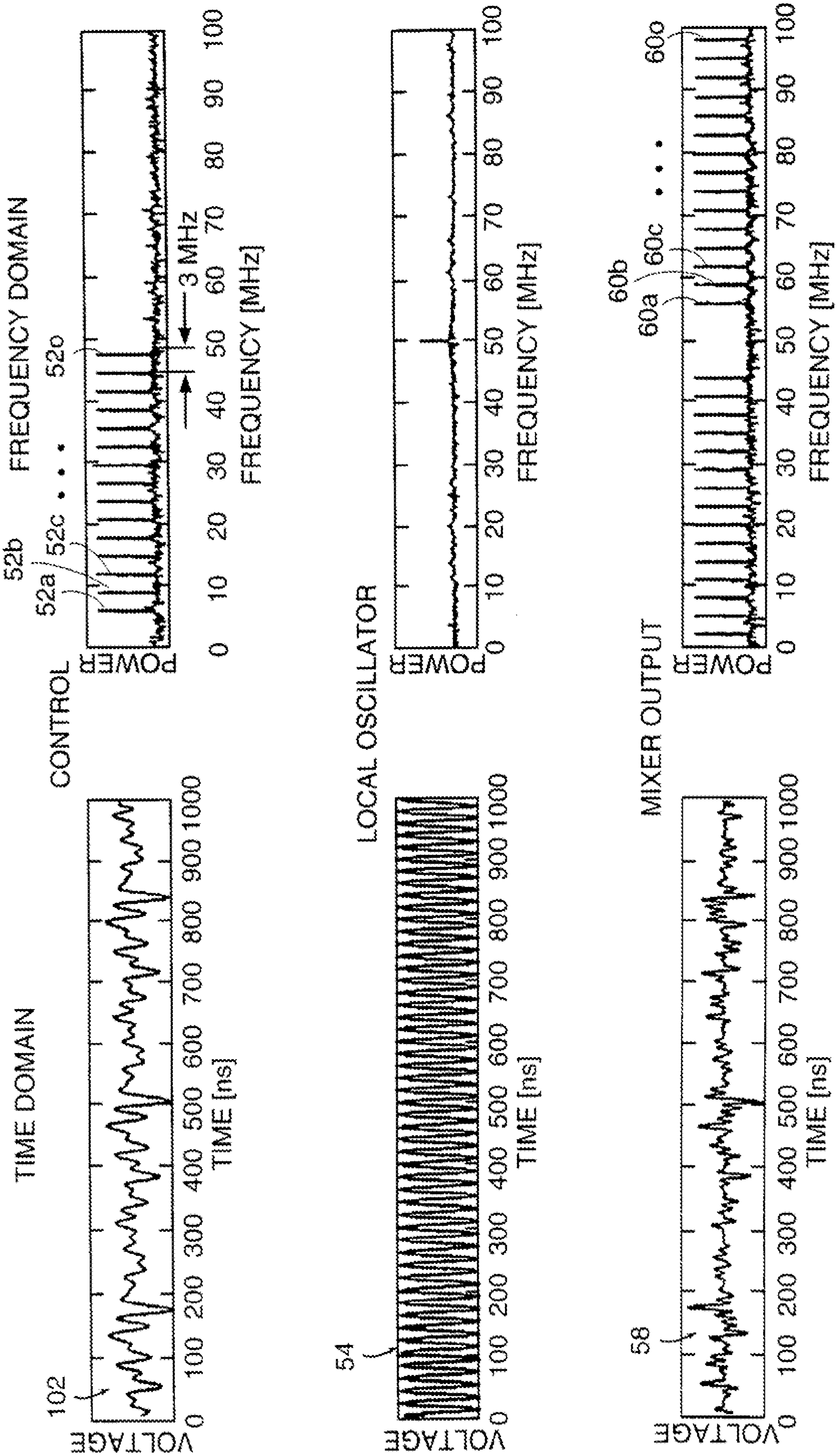
110
112
VIDEO MACRO LENS
FAN MIRROR ARRAY
94
RING MIRROR ARRAY
96
98
LASER DIODE 90
92
AOM 32
HIGH PASS FILTER
38
106 POWER AMPLIFIER
58
104 ACTIVE MIXER
DIGITAL RF SYNTHESIZER
100
GATE
54 LOCAL OSC
102 CONTROL

FIG. 7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FREQUENCY DOMAIN
CONTROL
LOCAL OSCILLATOR
MIXER OUTPUT
VOLTAGE
POWER
TIME [ns]
FREQUENCY [MHz]
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0 10 20 30 40 50 60 70 80 90 100
102
54
58
52a
52b
52c
52o
3 MHz
60a
60b
60c
60o

FIG. 8

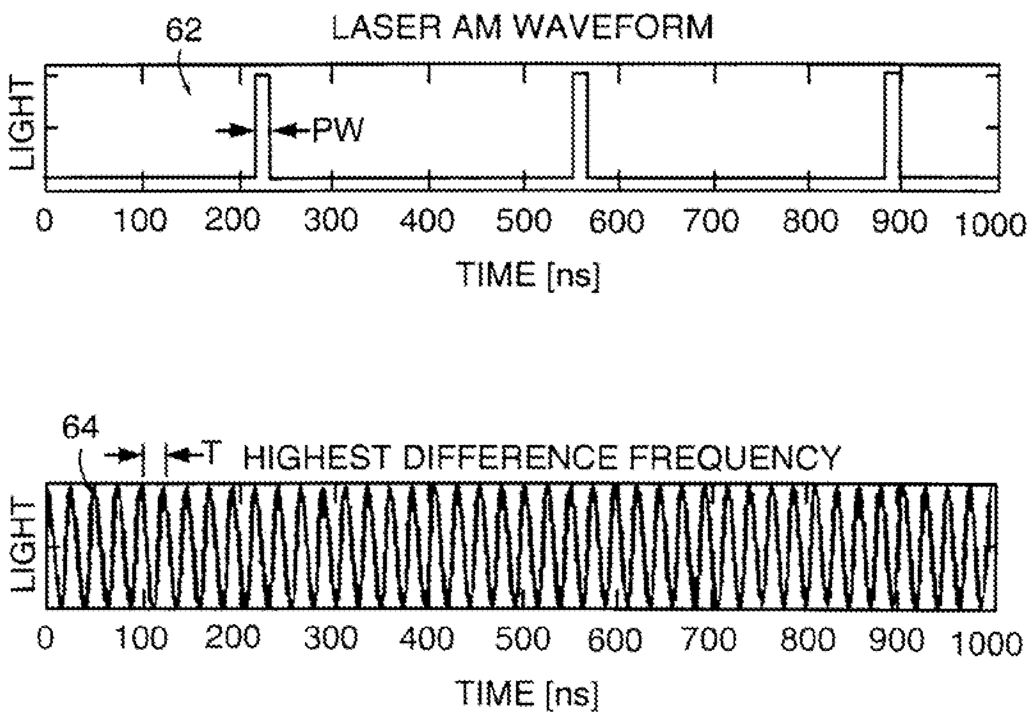
62
LASER AM WAVEFORM
LIGHT
PW
0 100 200 300 400 500 600 700 800 900 1000
TIME [ns]
64
T
HIGHEST DIFFERENCE FREQUENCY
LIGHT
0 100 200 300 400 500 600 700 800 900 1000
TIME [ns]

FIG. 9

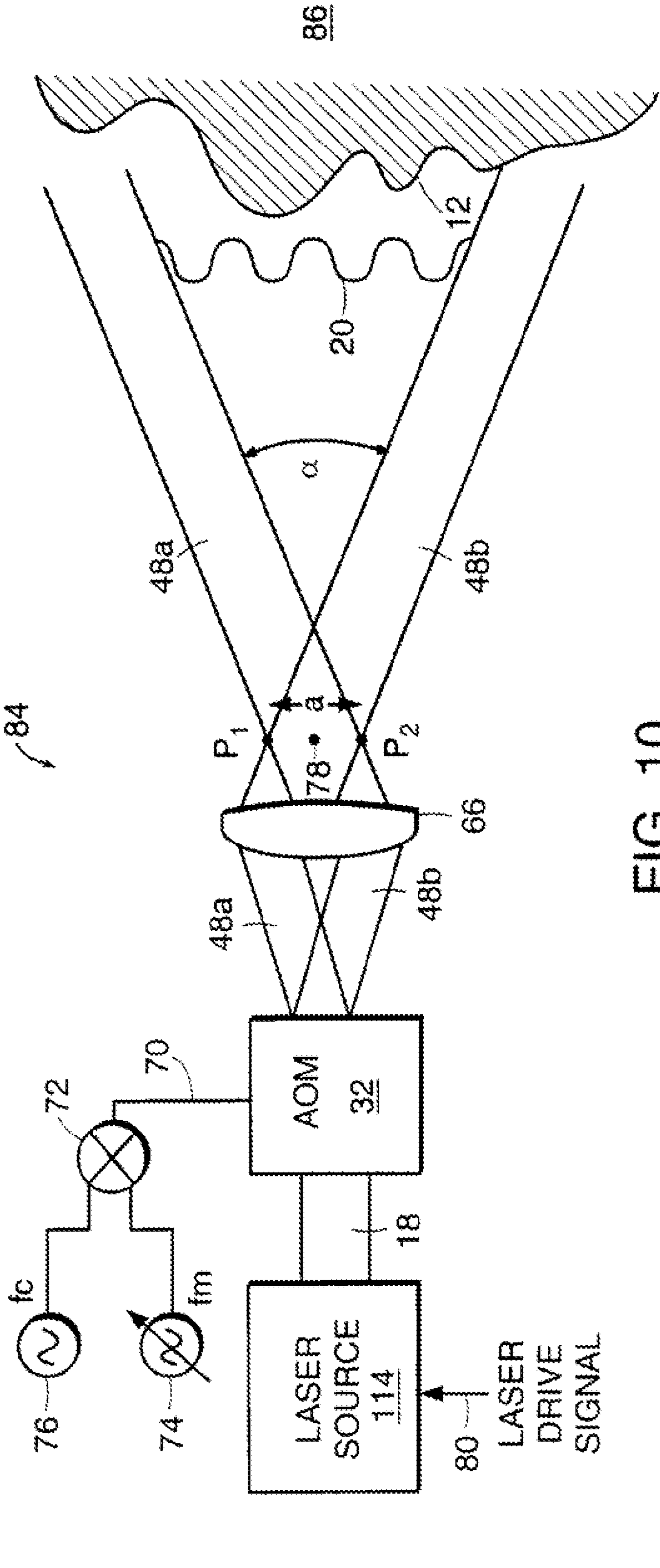
86
12
20
α
48a
48b
84
P_1
a
P_2
78
66
AOM
32
70
72
fc
fm
76
74
LASER
SOURCE
114
18
80
LASER
DRIVE
SIGNAL

FIG. 10

INTERNATIONAL SEARCH REPORT

International Application No
PCT/US 00/17097

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 G03F7/20 G02F1/33

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 G03F G02F

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, PAJ, WPI Data, INSPEC, COMPENDEX

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 4 796 038 A (ALLEN PAUL C ET AL) 3 January 1989 (1989-01-03) column 3, line 47 - line 49 column 7, line 12 - line 13 column 7, line 30 - line 32 figure 1	1-6, 14-19
X	PATENT ABSTRACTS OF JAPAN vol. 1998, no. 14, 31 December 1998 (1998-12-31) & JP 10 239015 A (NIKON CORP), 11 September 1998 (1998-09-11) abstract	1,2,5,6, 14,15, 17-19,21
A	US 4 496 216 A (COWAN JAMES J) 29 January 1985 (1985-01-29) abstract; figure 13	1-22

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[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

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Date of the actual completion of the international search	Date of mailing of the international search report
6 October 2000	16/10/2000

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Gill, R

1

INTERNATIONAL SEARCH REPORT

Inte   ional Application No
PCT/US 00/17097

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication,where appropriate, of the relevant passages	Relevant to claim No.
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1

Form PCT/ISA/210 (continuation of second sheet) (July 1992)

INTERNATIONAL SEARCH REPORT

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